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Rapid Communication

Planetary Imaging in Powers of Ten: A Multiscale, Multipurpose Astrobiological Imager

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Abstract

Contextual, multiscale astrobiological imaging is necessary to discover, map, and image patchy microbial colonization in extreme environments on planetary surfaces. The large difference in scale—several orders of magnitude—between search environment and microorganisms or microbial communities represents a challenge, which to date no single imaging instrument is able to overcome. In support of future planetary reconnaissance missions, we introduce an adapter-based imager, built from an off-the-shelf consumer digital camera, that offers scalable imaging ranging from macroscopic (meters per pixel) to microscopic (micrometers per pixel) imaging, that is, spanning at least 6 orders of magnitude. Magnification in digital cameras is governed by (1) the native resolution of the CCD/CMOS chip of the camera, (2) the distance between camera and object to be imaged (focal length), and (3) the built-in optical and digital zoom. Both telezoom and macro mode alone are usually insufficient for microscopic imaging. Therefore, the focal distance has to be shortened, and the native CCD resolution of the camera has to be increased to attain a microscopic imaging capability. Our adapter-based imager bridges the gap between macroscopic and microscopic imaging, thereby enabling for the first time contextual astrobiological imaging with the same instrument. Real-world applications for astrobiology and planetary geology are discussed, and proof-of-concept imagery taken with our prototype is presented. Key Words: Multiscale imaging—Contextual imaging—Microscopic imaging—Macroscopic imaging—Astrobiology—Microbes—Microbial communities—Endolithic Microorganisms. Astrobiology 13, 1005–1010.

1. Introduction

The search for life on Mars, in essence, entails the proverbial needle in the haystack: looking for microscopic organisms on an entire planet. The large difference in scale—several orders of magnitude—between search environment and microorganisms or microbial communities represents a challenge, which to date no single imaging instrument is able to overcome. To make matters worse, the spatial distribution of life in extreme environments is usually not uniform but patchy. For instance, in the McMurdo Dry Valleys, Antarctica, cyanobacteria and lichens survive under the surfaces of sandstone (Friedmann and Ocampo, 1976; Friedmann, 1982). However, not all available sandstone outcrops are colonized (Friedmann and Weed, 1987). Within a single boulder, not all facets are conducive to life, either due to too much or too little snow (Sun, 2013). On Earth, we can study life despite the spatial variability because we have an imager at each scale: the eyes of a field biologist, the hand lens, the dissecting microscope, and the compound light microscope. To do the same on Mars with a rover, however, it would be desirable to have a single imager that can cover all four spatial scales.

In this paper we describe a reconfigurable, adapter-based imager, built from an off-the-shelf consumer digital camera, that offers a scalable imaging capability ranging from macroscopic (meters per pixel) to microscopic (micrometers per pixel) imaging, that is, spanning more than 6 orders of magnitude spatially, analogous to "Powers of Ten"™ (http://www.youtube.com/watch?v=0fKBhvDjuy0). This adapter-based imager bridges the gap between macroscopic and microscopic imaging, thereby enabling for the first time the imaging of microbial communities and their local to regional to global context with the same instrument.

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2. Technical Implementation and Imaging Capabilities

Most commercial-off-the-shelf (COTS) digital cameras are in the megapixel class (routinely in excess of 5 MegaPixel). The majority of magnification attainable with digital cameras is governed by two factors: (1) the native resolution of the CCD/CMOS chip of the camera (*i.e.*, number of pixels) and (2) the distance between the camera and the object to be imaged (*i.e.*, focal length). Digital cameras (Fig. 1) have both optical and digital (*i.e.*, interpolation) zooming capabilities to allow for wide-angle to telezoom imaging. In addition, most digital cameras possess a macro mode for imaging up close, usually from a distance of around 20 cm from the object.

To add a microscope-like imaging capability to a digital camera, both the telezoom and the macro mode are insufficient, because the object cannot be magnified enough by placing the camera sufficiently close to the object and/or by magnifying the object with a zoom. Therefore, to attain microscopic imaging, the focal distance has to be shortened while the native CCD resolution of the camera ideally should be increased.

As proof of concept, a digital camera has been provided with a microscope-like imaging capability (Fink *et al.*, 2007b; Tarbell and Fink, 2008). The prototype comprises a 5 MegaPixel (MP) COTS digital camera that has been equipped with custom adapter, custom macro lens, illumination assembly, and foam spacer (Fig. 1a–1c). With this assembly, it is currently possible to place the COTS 5 MP camera within a focal distance of 1–5 cm from the object while still using the built-in autofocus for extreme close-up imaging. To obtain further magnified microscopic images, the optical zoom or, in addition, the digital zoom can be fully engaged.

With the optical zoom engaged, the prototype currently achieves a resolution of about 5 μm per pixel when placed 1–5 cm from the object. With the additional digital zoom, it achieves a pseudo-resolution (*i.e.*, software-calculated, non-optical resolution) of about 1.2 μm per pixel across a 2560 (h) $\times$ 1920 (v) pixel (*i.e.*, 5 MP) image. Although the digital zoom is realized by software-based interpolation rather than optically, it shows what imaging resolutions are potentially achievable with readily available COTS digital cameras of $>$20 MP (note: at present even smartphones possess cameras with $>$8 MP resolutions).

Higher resolutions/magnifications can be obtained by using larger CCD/CMOS chips, that is, more pixels, and/or different lens systems attached to the adapter. This adapter assembly is generic and can be custom-tailored to a multitude of digital cameras. It can be mounted on the protruding lens of a camera or to the nonmoving body of the camera around the lens, leaving space inside for the actual lens to protrude and to perform (auto)focusing and zooming operations. The adapter may also be mounted magnetically, and so on. Once the adapter is in place, arbitrary lens systems can be mounted to the adapter in addition to the built-in optics of the camera. The above was also detailed by Fink (2009, 2010).

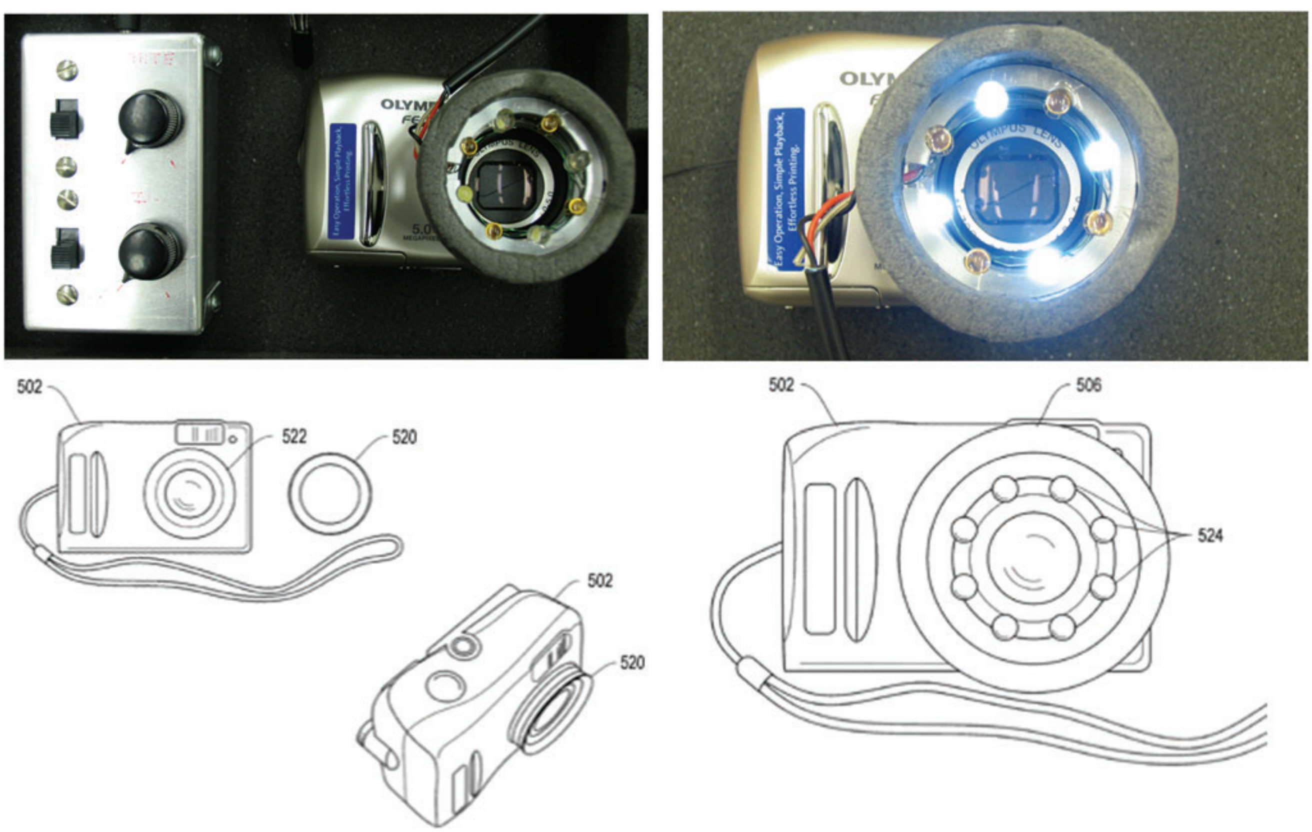

FIG. 1. Proof-of-concept contextual, multiscale astrobiological imager with macroscopic to microscopic imaging capability: the prototype comprises a (5 MP, 2560 $\times$ 1920 pixel) COTS digital camera that has been equipped with custom adapter, custom magnifying lens assembly, illumination assembly, and foam spacer to shield the optics from ambient light (Fink *et al.*, 2007b; Tarbell and Fink, 2008; Fink, 2009, 2010). Color images available online at www.liebertonline.com/ast

One of the main advantages of the camera is that various imaging needs can be met simply by switching the optical lens assemblies in front of the camera body (*e.g.*, by using a lens wheel). For example, extreme wide-angle (fisheye) imaging can be achieved with the same digital camera by using a wide-angle lens. Potential warping of the image can be eliminated by using a rectilinear wide-angle lens.

For close-up imaging an object (*e.g.*, planetary soil or rock), a spacer can be mounted around the adapter and the magnifying lens assembly to shield the optics from ambient light (*e.g.*, for the detection of chemiluminescence). Inside that spacer, well-defined artificial illumination sources, such as LEDs, can be placed either directly or in a diffuse, indirect manner to illuminate the object. These illumination sources may comprise but are not limited to UV, for potentially inducing fluorescence, and polarized light [*e.g.*, using polarized light-emitting diodes (Matioli *et al.*, 2012)]. If the object exhibits disturbing glare due to the illumination, polarized filters can be used in front of the lens to filter out the glare. The use of well-defined illumination sources (*i.e.*, well-defined wavelengths and spectra) inside the spacer would allow for the determination of true colors of objects. True reflectance spectra could be obtained the same way if the camera was replaced with a spectrometer (*e.g.*, Bearman *et al.*, 2007; Johnson *et al.*, 2007).

3. Field Testing

On Earth, the search for new endolithic communities is typically a two-step process. First, a regional geological map is consulted to determine the availability of outcrops of suitable lithology: sandstone, gypsum, halite, and so on (Friedmann, 1980; Wierzchos *et al.*, 2006; Dong *et al.*, 2007; Sun *et al.*, 2010). Next, a field expedition is conducted to determine whether the outcrops are actually colonized, as well as to collect samples for subsequent taxonomical identification in the laboratory. On Mars, high-resolution remote sensing data from previous missions would be consulted to select sites for *in situ* investigation by a rover. As part of this study, we field tested the astrobiological imager in the Mojave Desert to demonstrate how it would benefit an *in situ* search on Mars.

Sandstone outcrops of Jurassic age occur in the eastern Mojave Desert. Ongoing investigations by one of us (Sun) have revealed that these rocks are colonized by cryptoendolithic lichens. This system is, in many aspects, similar to the cryptoendolithic lichens that colonize sandstone in the mountainous regions of the McMurdo Dry Valleys. Akin to a colonized Antarctic sandstone, the Mojave Desert sandstone is commonly stained by a ferromanganese oxide–rich veneer known as rock varnish. Where the rock is colonized, however, biological activity results in continuous exfoliation or erosion of the rock surface, preventing a thick mature varnish from forming. Instead, biological exfoliation results in a terraced surface topology. Sometimes, the exfoliation crusts are iron-stained and oxidized to varying degrees, as white, yellow, and red. Unlike in Antarctica, where no fruiting bodies manifest on the surface except in exceptionally well-protected niches, fruiting bodies are common in the Mojave Desert.

All major characteristics of the Mojave Desert system were detected with the imager. From about a hundred meters away, the outcrops and their surface exfoliation could be detected (Fig. 2a). Conceivably, a spectrometer mounted on the same rover could verify the sandstone lithology. Upon approach to within 10 m, the presence of varnished and unvarnished areas could be seen on the same boulder (Fig. 2b). Placing the imager 1 m above the rock, the exfoliation pattern of the unvarnished part of the sandstone was ascertained (Fig. 2c). Placing the imager against the rock, the presence of the black fruiting bodies became visible at a resolution of about 5 μm per pixel (Fig. 2d). Finally, the presence of a chlorophyll-rich, colonized zone just under the rock surface was verified by inspecting a fractured rock sample at various magnifications ranging from about 12 μm (Fig. 2e) down to about 1.2 μm per pixel (Fig. 2f).

4. Results and Applications

The comparison and analysis of images at multiple scales and resolutions enable the localization, detection, and identification of life-bearing locales (*e.g.*, patches) through nested imaging from a macroscopic to a microscopic context. As shown in Fig. 2, obtained images range from wide-angle imaging (Fig. 2a) with a resolution of meters per pixel down to microscopic imaging (Fig. 2f) with a micrometer resolution per pixel, thus spanning 6 orders of magnitude while using the same camera. However, the example given above is only one of many applications. The availability of a multiscale multipurpose astrobiological imager as described above will also affect the exploration strategy for a planet like Mars, especially in light of NASA's plans for a (rover) mission to Mars, which is to be launched in July or August 2020.

This type of multipurpose and reconfigurable instrument may render future missions more cost-effective, and together with automated feature extraction and science goal prioritization software packages (*e.g.*, Fink, 2006; Fink *et al.*, 2008a), is ideally suited for tier-scalable reconnaissance missions (Fink *et al.*, 2005, 2007a, 2008b; Noor *et al.*, 2007; Kean, 2010) that enable not only simultaneous exploration from different vantage points (*e.g.*, space, atmospheric, surface, and subsurface exploration) but also a "zoom-in" capability ranging from global to regional to local reconnaissance.

For example, on a macroscopic scale we would recommend to focus on large-scale erosional features and depositional environments, which are consistent with life processes based on analog sites on Earth (Mahaney *et al.*, 2004, 2012, 2013; Wierzchos *et al.*, 2006; Sun *et al.*, 2010; Schulze-Makuch *et al.*, 2013). Rates and types of erosion consistent with biological processes were suggested as a geosignature for life by Schulze-Makuch and Irwin (2008), and current Mars exploration is targeting depositional environments that involved water (such as lake shores and ancient lake beds). After identifying the larger-scale structures, the next step would be to identify the cause of erosion by examining sedimentary layers and determine the rock and mineral composition of these features. On an even smaller-scale, evidence for bioturbations, biofilms and microbial filaments might be found, while in the ancient lake deposits fossil life might be uncovered. Thus, employing this approach, the "user" (*e.g.*, planetary rover) of the astrobiological imager would zoom in from large-scale

FIG. 2. Series of images taken of a sandstone outcrop in the Mojave Desert. (**a**) A sandstone outcrop as viewed from about 100 m, with no adapter-based lens mounted and no zoom engaged: at this distance rock weathering is evident. (**b**) From about 10 m distance with no adapter-based lens mounted and no zoom engaged: exfoliative rock weathering and potential varnish formation is observed. (**c**) From about 1 m distance with no adapter-based lens mounted and no zoom engaged: fruiting bodies produced by endolithic lichens are evident on exfoliated areas but not varnished areas. (**d**) With adapter-based lens mounted at about 5 μm resolution per pixel with optical zoom engaged: permitting a close-up view of the lichen fruiting bodies. (**e**) With adapter-based lens mounted at about 12 μm resolution per pixel with no zoom engaged: the presence of a green (chlorophyll), colonized zone below the surface is identified. (**f**) With adapter-based lens mounted at about 1.2 μm resolution per pixel with optical and digital zoom engaged: permitting a close examination of relationship between sand grains and biomass. Color images available online at www.liebertonline.com/ast

structures to small-scale structures over many orders of magnitude and attempt to discern during each step whether the observed features are consistent with life and life processes, or alternatively by which type of inorganic processes they are caused.

5. Conclusions

Based on our field testing, we have demonstrated an adapter-based capability to (re)use the same digital camera for imaging that ranges from a macroscopic (meter resolution per pixel) to a microscopic (micrometer resolution per pixel) scale, thus spanning 6 orders of magnitude. During a planetary reconnaissance mission, such a capability could be realized through a lens wheel, akin to microscope lenses, in front of the camera body, such that lenses or lens systems would automatically be swapped *in situ*. Such a multiscale imager may be deployed on (Mars) rovers, landers, and potentially airborne platforms such as blimps that may have the capability of stand-off and *in situ* sensing.

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Author Disclosure Statement

Fink may have proprietary interest in the underlying adapter-based microscopic imaging technology as patents on behalf of the California Institute of Technology are issued. Sun, Mahaney, Kuhlman, and Schulze-Makuch have no proprietary interest.

Abbreviations

COTS, commercial-off-the-shelf; MP, MegaPixel.

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